Analysing Consolidation Data to Optimise Elastic Visco–plastic Model Parameters for Soft Clay

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CERTIFICATE OF ORIGINAL AUTHORSHIP

I certify that the work in this thesis has not previously been submitted for a degree nor has it been submitted as part of requirements for a degree except as fully acknowledged within the text.

I also certify that the thesis has been written by me. Any help that I have received in my research work and the preparation of the thesis itself has been acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

Thu Minh Le

Feburary 2015

ABSTRACT

Analysing the behaviour of soft soils under embankments is a significant challenging task for geotechnical engineers. By having more insight into long term soil behaviour and understanding the key parameters influencing the results, there will be more chance to strategically plan and utilise the soft ground for construction purposes. The time–dependent behaviour of soft soils, especially the ground settlements under structural and non–structural loading, is considered as a significant issue, which has been studied for many decades. Prediction of creep settlement of soft soils is a challenging task, as a very long period of time counted in years is involved. Many theories have been proposed along with a large number of laboratory and field measurements in order to provide more precise knowledge of the time–dependent viscous behaviour of soft soils. However, there are still some disagreements between theoretical and practical studies, which may keep the accuracy of the predictions questionable.

Among the great number of developed models for soft soils, the elastic visco–plastic model with the non–linear creep function is considered as an effective method to describe the long–term stress–strain behaviour of soft soils. However, the difficulties to determine the model parameters limit the application of the model in practice. Since the relationship between the effective stress and strain during the dissipation of the excess pore water pressure cannot be identified easily, in the current practice the creep strain limit ε_{lm}^{vp} and the creep coefficient ψ_o/V to form the creep function are determined based on the curve fitting of the experimental data after the end of the primary consolidation. As a result, the number of data points available for the curve fitting is limited, and the extremely long tests are required. Moreover, in the conventional procedure for the ease of the curve fitting, the time parameter t_o in the elastic visco–plastic, which is the time value of the reference time line in the space of ε-$log(\sigma'_z)$, has been assumed as the time at the end of primary consolidation process. Hence, based on this assumption of t_o, the reference time line would include viscous strain, which is contradict to the definition of a viscous free reference time line. Thus, the value of t_o influences not only the reference time line parameters, but also the parameters of the creep function. Additionally, the conventional determination approach for the model parameters is influenced by the thickness of the soil sample. Hence, the model parameters obtained by the conventional method may not be unique.

As a result, the main objective of this research project is to propose a numerical solution to determine the model parameters for the elastic visco–plastic model adopting the trust–region reflective least square algorithm. The trust-region reflective least square algorithm is an advanced optimisation method for the non-linear equation system. A Crank–Nicolson finite difference scheme is applied to solve the coupled partial differential equations in order to simulate one-dimensional stress-strain behaviour of soft soil with different boundary conditions. The proposed method can adopt the experimental data during the dissipation of the excess pore water pressure to determine all the model parameters simultaneously.

In this thesis, a series of laboratory experiments were conducted at the UTS soil laboratory using two sizes of hydraulic consolidation Rowe cell setups. A 29.5 mm thick soil sample of a kaolinite mixture was tested and adopted to determine the model parameters, while an experimental result of a thicker soil sample (i.e. 140.5 mm thick) was compared with the predictions using the optimised model parameters. The Rowe cell setups can measure the volume change, the vertical settlement and the excess pore water pressure continuously. Especially, the large Rowe cell setup to conduct the test on the 140.5 mm thick soil sample was modified to measure the excess pore water pressure at different depth and different distances to the centre line at the base. Moreover, other four validation exercises including two laboratory–based case studies and two field–based case studies were included to verify the ability of the proposed method to analyse the time-dependent behaviour of soft soils.

The developed method can be considered as a simple, practical and accurate solution for the model parameter determination. The optimised model parameters allow the predictions of settlement to be in good agreement with the measurements, while the predictions of the excess pore water pressure are reasonably close to the measurement. Additionally, the variations of the creep strain limit, the creep coefficient and the creep strain rate during the dissipation of the excess pore water pressure can be observed. Moreover, the unusual increase of the excess pore water pressure in the early stages of loading can be also predicted. The numerical analysis applying the proposed method is able to illustrate the influence of the soil layer thickness on the time–dependent stress-strain behaviour of soft soil. The proposed approach can be adopted to back calculate the elastic visco-plastic model parameters for real case in the field utilising time-dependent settlement and excess pore water pressure measurements.

To my father, *Pha Van Le*, my mother, *The Thanh T. Truong*, my brother, *Tri Minh Le* and my husband, *Thanh Tien Nguyen*, whose love, encouragement and support have been always with me through this journey.

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LIST OF PUBLICATIONS

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❖ **Submitted Journal Papers**

Trust-region Reflective Optimisation to Obtain Soil Visco-plastic Properties, *Engineering Computations*

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LIST OF NOTATIONS

English letters

A	Model parameter in Singh and Mitchell (1968)
a	Function coefficient of creep strain limit
a'	Relation of instantaneous compression and effective stress in Taylor & Merchant (1940) concept
a_f	Relation between void ratio and effective stress in Taylor & Merchant (1940) concept
B	Strip width
BP	Back pressure
b	Function coefficient of creep strain limit
b	Haft of a strip width
CB	Control box of IVC
CGT	Controlled gradient test
CL	Centre line
CP	Cell pressure
CRS	Constant rate of strain
C_c	Compression index
C_{ijkl}	Elastic matrix
C_r	Recompression index
C_α	Coefficient of secondary compression
$C_{\alpha max}$	Positive constant in Karim et al. (2010)
C_α^*	Non constant creep coefficient in Karim et al. (2010)
$C_{\varepsilon c}$	Compressibility ratio
$C_{\alpha e}$	Coefficient of secondary compression based on void ratio
$C_{\alpha\varepsilon}$	Coefficient of secondary compression based on vertical strain
c	Function coefficient of creep coefficient
c_k	Coefficient of permeability change index
c_v	Coefficient of consolidation
$(c_v)_{(i,j)}$	Coefficient of consolidation at coordinator (i,j)
D	Diagonal scaling matrix
DL	Data logger
d	Function coefficient of creep coefficient
EOP	End of primary consolidation
EVP	Elastic visco-plastic
E_{act}	Activation energy
e	Void ratio
e_o	Initial void ratio
e_{EOP}	Void ratio at the end of primary consolidation
$\dot{e}$	Rate of change in void ratio
$\dot{e}_{\sigma'}$	Change of void ratio with respect of the effective stress at an instant time t
$\dot{e}_t$	Change of void ratio with time at a constant effective stress
$F(x)$	Vector valued function having the i^{th} component equal to $f_i(x)$
f_n	Normal force
f_t	Tangential force
$f(x)$	Objective function of optimisation procedure
$f_i(x)$	Function value at time i
G_s	Specific gravity
g	Potential function
g	Gradient of $f(x)$ for the current x
$g(\varepsilon_z, \sigma'_z)$	Creep strain rate
$\left(g(\varepsilon_z, \sigma'_z)\right)_{(i,j)}$	Creep strain rate at coordinator (i,j)
H	Maximum drainage distance

H	Symmetric matrix of second derivatives in trust-region algorithm
H_o	Initial soil layer thickness
H_{EOP}	Soil thickness at the end of primary consolidation
h_z	Soil depth
KBS	Kaolinite – bentonite – fine sand mixture
K_o	Lateral earth pressure at rest
k	Coefficient of vertical permeability at coordinator (i,j)
$(k)_{(i,j)}$	Coefficient of vertical permeability
k_o	Initial coefficient of vertical permeability
I_z	Influence factor
IL	Incremental loading
IVC	Infinite volume controller
J	Jacobian of F
LL	Liquid limit
LPDT	Linear potentiometer displacement transducer
LRC	Large Rowe cell
MSL_{24}	Multiple stage loading with increments every 24 hours
MSL_p	Multiple stage loading with increments at the end of primary consolidation
m	Model parameter in Singh & Mitchell (1968)
m_v	Coefficient of volume compressibility
$(m_v)_{(i,j)}$	Coefficient of volume compressibility at coordinator (i,j)
N	Trust region of current point x
N	Positive constant in Karim et al. (2010)
N	Specific volume of a soil normally isotropic consolidated at lnp' value of zero
NC	Normally consolidated
N_{SPT}	SPT blow count
OC	Overconsolidated
OCR	Overconsolidation ratio
PC	Computer
PI	Plasticity index
PVC_p	Primary pressure/volume controller
PVC_s	Secondary pressure/volume controller
PWP	Pore water pressure
PWPT	Pore water pressure transducer
p'	Mean effective stress
p'_e	Equivalent pressure
p_L	Creep exclusion preconsolidation pressure in Karim et al. (2010)
$\bar{p}_o$	Creep inclusive preconsolidation pressure in Karim et al. (2010)
q	Deviator stress at time t
$\bar{q}$	Deviator stress level in Singh & Mitchell (1968)
q_o	Initial deviator stress
q_o	Uniform applied stress caused by test fill
$q(s)$	Approximation function of objective function $f(x)$
R	Time resistance
R_s	Time resistance after end of primary consolidation
R^2	Coefficient of determination
r_s	Creep resistance
SM	Settlement marker
SPT	Standard penetration test
SRC	Small Rowe cell
S	Two–dimensional subspace of s
S_c	Secondary compression or creep compression

S_p	Primary compression
S_t, S_j	Surface settlement at time t
S_u	Undrained shear strength
s	Trial step of x
$\dot{s}$	Sliding velocity
T	Absolute temperature
T_v	Unitless time factor
TRRLS	Trust-region reflective least squares
t	Elapsed loading time
t'	Difference between τ and t_c
t_o	Time parameter
t_c	Time at conventional end of primary consolidation
t_i	Time corresponding to the instant time-line in Garlanger (1972) or reference time in Singh & Mitchell (1968)
t_e	Equivalent time
t_r	Extrapolated time corresponding to R = 0
t_{tot}	Total loading time
t_{vp}	Visco-plastic (creep) time
t_{EOC}	Construction time
t_{EOP}	Time at the end of primary consolidation
U	Degree of consolidation
$u_{(i,j)}$	Excess pore water pressure at coordinator (i,j)
u_o	Initial excess pore water pressure in Taylor & Merchant (1940)
u_o	Hydrostatic pore water pressure, initial equilibrium water pressure
u_e	Excess pore water pressure
u_{ei}	Initial excess pore water pressure (=$\Delta\sigma_z$)
u_x	Excess pore water pressure at time t in Taylor & Merchant (1940)
$u(x)$	Total squares of difference between measured and predicted values
V	Specific volume corresponding to e_o
v	Specific volume of a soil at the normal stress p'
w_o	Initial water content
w_c, w	Water content
x	Vector of variable
y_i	Measured data point at time i
z	Soil depth
z_t	Compression per unit of layer thickness

Greek letters

Δ	Trust region radius > 0
Δt	Time step
Δz	Space step
α	Relationship between the logarithm of the preconsolidation pressure and the logarithm of the strain rate
$\bar{\alpha}$	Model parameter in Singh & Mitchell (1968)
α_p	Immediate settlement per unit of thickness and unit of load
α_s	Rate of secondary compression per unit thickness and load unit
$\Delta\sigma$	Load increment
$\Delta\sigma_z$	Applied stress increment
γ	Fluidity parameter
γ_s	Unit weight of soil
γ_w	Unit weight of water
ε_z	Vertical strain

ε_{zi}	Initial vertical strain
$(\varepsilon_z)_{(i,j)}$	Vertical strain at coordinator (i,j)
$(\varepsilon_{z\_ave})_t, (\varepsilon_{z\_ave})_j$	Average vertical strain at time t
ε_z^e	Vertical elastic strain
ε_{zo}^e	Vertical elastic strain at $\sigma'_z = \sigma'_u$
ε_{zo}^{ep}	Elastic plastic strain at $\sigma'_z = \sigma'_{zo}$
ε_z^p	Vertical plastic strain
ε_z^r	Vertical reference strain at σ'_z
$(\varepsilon_z^r)_{(i,j)}$	Vertical reference strain at σ'_z at coordinator (i,j)
ε_{zo}^r	Vertical reference strain at σ'_{zo}
ε_{lm}^{vp}	Creep strain limit
$(\varepsilon_{lm}^{vp})_{(i,j)}$	Creep strain limit at coordinator (i,j)
ε_z^{vp}	Visco-plastic (creep) strain
$\dot{\varepsilon}$	Strain rate
$\dot{\varepsilon}_c$	Creep strain rate
$\dot{\varepsilon}^e$	Elastic strain rate
$\dot{\varepsilon}^{vp}$	Visco-plastic strain rate
$\dot{\varepsilon}_z^{vp}$	Vertical visco-plastic (creep) strain rate
$\dot{\varepsilon}_p$	End of primary consolidation strain rate
$\dot{\varepsilon}_z^p$	Vertical plastic strain rate
κ/V	Elastic stiffness
λ	Slope of the normal isotropic consolidation line in the isotropic normal compression
λ/V	Elastic plastic stiffness
μ	Coefficient of secondary compression by Taylor & Merchant (1940)
μ*	Modified creep parameter
η	Coefficient of viscosity
σ_z, σ_{zi}	Total vertical stress
σ'_{ij}	Stress state
σ'_{po}	Preconsolidation pressure before loading
σ'_{pc}	Preconsolidation pressure
σ'_z	Vertical effective stress
$(\sigma'_z)_{(i,j)}$	Vertical effective stress at coordinator (i,j)
σ'_u	Unit vertical effective stress (i.e. 1 kPa)
σ'_{zi}	Initial vertical effective stress
σ'_{zo}	EVP model parameter, vertical effective stress corresponding to ε_{zo}^{ep}
σ'_{zf}	Final vertical effective stress
$\dot{\sigma}_{ij}$	Stress rate
$\dot{\sigma}_z$	Rate of change in effective stress
τ	Time parameter = 1 day
τ_c	Difference between t_c and t_r
ψ_o/V	Creep coefficient
ψ/V	Creep parameter